The use of an MEG device as a 3D digitizer and a motion correction system

J.C. de Munck, J.P.A. Verbunt, D. van ‘t Ent, and B.W. van Dijk

MEG Center, AZVU reception C, De Boelelaan 1117, 1081 HV Amsterdam

1. Abstract

An algorithm is described that localizes a set of simultaneously energized coils using MEG detectors. The algorithm is based on a mathematical model describing the coils as stationary magnetic dipoles, of which the source time functions are known. It is assumed that the source time functions are orthogonal. It is shown how this a priori knowledge can be used to improve the efficiency of the algorithm.

The method is useful for continuous or intermittent head position registration during long MEG sessions, to registrate MR and MEG data, to localize EEG electrodes attached to the head, when EEG and MEG are recorded simultaneously, and to digitize the head shape. Experimental data shows that the localization error can be smaller than 2 mm.

2. Introduction

Compared to Electro Encephalography (EEG) Magneto Encepalography (MEG) has the practical advantage that no electrodes need to be attached to the subject’s head. In particular, when many channels are recorded for source localization studies, this is an important practical advantage. The drawback is, however, that the subject can move his head with respect to the MEG sensors during the registration. For this reason it has been proposed [1,3] to attach coils on the head which are energized with a sine function. When these coils are localized by fitting a magnetic dipole function on the resulting MEG signals, the position of the head with respect to the sensor system can be determined. When this procedure is performed repeatedly, the movement of the head can be recorded and the data can be corrected using interpolation techniques.

In this paper a new variant of this head localization technique is described. Instead of using coil sets of three orthogonal coils [1,3] simple uncalibrated coils are used and the source time function of the currents are not restricted to sine waves, but can have any shape. Furthermore, the coils can be energized simultaneously. The proposed technique of localizing energized coils also has other applications. It can be used to project current dipoles, localized with MEG, onto an MR scan [2]. Furthermore, when three coils are fixed to the subject’s head, a fourth coil can be used to determine the shape of the head or the positions of EEG electrodes, when EEG and MEG are recorded simultaneously.

3. Methods

When the current activation function of coil k is denoted by $s_k(t_j)$ (or s_{kj}), and the resulting magnetic induction recorded from sensor i is denoted as $\tilde{b}_{ij}$, we have

$$\tilde{b}_{ij} = \sum_{k=0}^{K-1} s_{kj} \beta(\mathbf{x}_i, \mathbf{n}_i; \mathbf{m}_k, \mathbf{y}_k) \quad , i = 0,\ldots,I-1 \text{ and } j = 0,\ldots,J-1 .$$

Here, K is the number of coils, I is the number of sensors, J is the number of time samples and $\beta(\mathbf{x}_i, \mathbf{n}_i; \mathbf{m}_k, \mathbf{y}_k)$ is the magnetic induction caused by the k-th coil on sensor i. Furthermore, $\mathbf{x}_i$ and $\mathbf{n}_i$ are the position and orientation of the i-th MEG sensor and $\mathbf{m}_k$ and $\mathbf{y}_k$ represents the position and orientation of the k-th coil.

When it is assumed that the background noise is uncorrelated, the optimal estimator of the coils is obtained by minimizing H, the sum of squared differences between the model and the data. Herewith, it is assumed that the source time functions of the currents applied onto the coils are known, up to a constant factor, which appears as the magnitude of $\mathbf{m}_k$ in the equations. It is found that

$$H = \min_{\mathbf{m}_k, \mathbf{y}_k} \sum_{i} \left(\sum_{k_1 k_2} S_{k_1 k_2} \beta_i(\mathbf{m}_{k_1}, \mathbf{y}_{k_1}) \beta_i(\mathbf{m}_{k_2}, \mathbf{y}_{k_2}) - 2 \sum_{k} c_{ik} \beta_i(\mathbf{m}_k, \mathbf{y}_k) \right) + H_0$$

with

$$S_{k_1 k_2} \equiv \sum_{j=0}^{J-1} s_{k_1}(t_j) s_{k_2}(t_j), \ c_{ik} \equiv \sum_{j=0}^{J-1} b_{ij} s_k(t_j) \text{ and } H_0 \equiv \sum_{j,i=0}^{J-1,I-1} b_{ij}^2 .$$

Note that since the source time functions s_{kj} are known a priorily, the cross correlations of the source time functions S_{k1k2} and the cross correlations between the source time functions and the MEG signals c_{ik} can be computed in advance. As a result, no summations over time are required in the evaluation of the cost function and the speed of the algorithm is (almost) independent of J.

3.1 The optimal moment parameters

When minimizing the function H, one can use the fact that the coil moments are linear parameters. This implies that when the gradient of H is set to zero, a linear system of equations in $\mathbf{m}^{\mathrm{T}} \equiv (\mathbf{m}_0{}^{\mathrm{T}}, \mathbf{m}_1{}^{\mathrm{T}},\ldots,\mathbf{m}_{\mathrm{K}-1}{}^{\mathrm{T}})$, is obtained:

$$\sum_{k_1} S_{k_1 k_2} \sum_{\mathrm{i}}^{\mathrm{I}} \left(\frac{\partial \beta_i(\mathbf{y}_{k_2})}{\partial \mathbf{m}_{k_2}} \frac{\partial \beta_i(\mathbf{y}_{k_1})}{\partial \mathbf{m}_{k_1}} \right) \mathbf{m}_{k_1} = \sum_{\mathrm{i}}^{\mathrm{I}} c_{ik_2} \frac{\partial \beta_i(\mathbf{y}_{k_2})}{\partial \mathbf{m}_{k_2}} \quad , k_2 = 0,\ldots,K-1$$

or

$$A\mathbf{m} = \mathbf{b}.$$

With the same notation the non-linear part of the minimization can be expressed as:

$$H = \min_{\mathbf{y}_k} -\mathbf{m}^{\mathrm{T}}\mathbf{b} + H_0 \, .$$

With this expression for H, additional summations over i are avoided.

3.2 Orthogonal time functions

When the applied currents are devised in such a way that the source time functions are mutually orthogonal the matrix A becomes

$$\{A\}_{3\mathrm{k}_1+l_1,3\mathrm{k}_2+l_2} = \delta_{k_1k_2} S_{k_1k_1} \sum_{\mathrm{i}}^{\mathrm{I}} \left(\left\{ \frac{\partial \beta_i(\mathbf{y}_{k_1})}{\partial \mathbf{m}_{k_1}} \right\}_{l_1} \left\{ \frac{\partial \beta_i(\mathbf{y}_{k_1})}{\partial \mathbf{m}_{k_1}} \right\}_{l_2} \right)$$

$$= \begin{pmatrix} A_0 & \varnothing & \varnothing & \varnothing \\ \varnothing & A_1 & \varnothing & \varnothing \\ \varnothing & \varnothing & \ldots & \varnothing \\ \varnothing & \varnothing & \varnothing & A_{\mathrm{K}-1} \end{pmatrix}$$

with

$$\{\mathrm{A}_{\mathrm{k}}\}_{l_1,l_2} \equiv S_{kk} \sum_{\mathrm{i}}^{\mathrm{I}} \left(\left\{ \frac{\partial \beta_i(\mathbf{y}_k)}{\partial \mathbf{m}_k} \right\}_{l_1} \left\{ \frac{\partial \beta_i(\mathbf{y}_k)}{\partial \mathbf{m}_k} \right\}_{l_2} \right)$$

and the vector $\mathbf{b}$ can be expressed as $\mathbf{b}^{\mathrm{T}} = (\mathbf{b}_0{}^{\mathrm{T}},\ldots, \mathbf{b}_{\mathrm{K}-1}{}^{\mathrm{T}})$. Under these conditions one obtains for the residual function H

$$H = \sum_{\mathrm{k}=0}^{\mathrm{K}-1} \min_{\mathbf{y}_k} (-\mathbf{b}_k{}^{\mathrm{T}} A_k{}^{\mathrm{inv}} \mathbf{b}_k) + H_0 \, .$$

The cost function is split in separate terms, which depend on one coil. Therefore, when the source time functions are mutually orthogonal, solving a minimization problem for each of the coils independently solves the minimization problem for all coils.

3.3 Adding a pointing tip to the fourth coil

One of the applications of our coil localization algorithm is to attach three coils to the head, e.g. in front of both ears and at the nasion, and to use the fourth coil to localize EEG electrodes or to measure the shape of the head. Since the dimension of the coil (ca. 5 mm) is larger than the required and expected accuracy of the localization algorithm it is useful to add a pointing tip onto the fourth coil, which points to the measurement point. When the length l of the tip is known and one has localized the center $\mathbf{y}$ and the orientation $\hat{\mathbf{m}} \equiv \mathbf{m}/|\mathbf{m}|$ of the coil, one can compute the position $\mathbf{t}$ of the tip using $\mathbf{t} = \mathbf{y} + l\,\hat{\mathbf{m}}$.

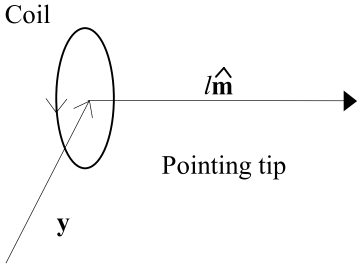

Figure 1. *When a pointing tip is attached to the fourth coil, a better defined spot is obtained.*

To transform this point to a coordinate system fixed to the head, with the origin halfway between left and right ears, the x-axis pointing to the nasion and y-axis pointing to the left ear and the z-axis is perpendicular to these axes, we use the following transformation:

$$\mathbf{t'} = \sum_{k=0,1,2} \hat{\mathbf{x}}_k \cdot \left(\mathbf{t} - .5(\mathbf{y}_L + \mathbf{y}_R)\right) \hat{\mathbf{x}}_k$$

and

$$\mathbf{m'} = \sum_{k=0,1,2} \hat{\mathbf{x}}_k \cdot \mathbf{m}\, \hat{\mathbf{x}}_k$$

with

$$\hat{\mathbf{x}}_0 = \frac{\mathbf{y}_N - .5(\mathbf{y}_L + \mathbf{y}_R)}{|\mathbf{y}_N - .5(\mathbf{y}_L + \mathbf{y}_R)|}$$

$$\hat{\mathbf{x}}_1 = \frac{\hat{\mathbf{x}}_0 \times \left(\hat{\mathbf{x}}_0 \times \left(\mathbf{y}_N - .5(\mathbf{y}_L + \mathbf{y}_R)\right)\right)}{\left|\hat{\mathbf{x}}_0 \times \left(\hat{\mathbf{x}}_0 \times \left(\mathbf{y}_N - .5(\mathbf{y}_L + \mathbf{y}_R)\right)\right)\right|} \, .$$

$$\hat{\mathbf{x}}_2 = \hat{\mathbf{x}}_0 \times \hat{\mathbf{x}}_1$$

Here $\mathbf{y}_{\mathrm{N}}$, $\mathbf{y}_{\mathrm{L}}$ and $\mathbf{y}_{\mathrm{R}}$ are the positions of the nasion, the left and right pre aucular points, respectively.

4. Results

The localization of the coils with the method described above will be demonstrated with a few examples. The MEG system present at our lab is a whole helmet system of CTF Systems Inc. with 151 gradiometers with a baseline of 5 cm. The noise level of the SQUIDS is about 10 fT/√Hz. The MEG system is placed inside a three layered magnetically shielded room. In all experiments, the coils are energized during 2 s and the resulting magnetic fields are sampled at a rate of 1250 Hz. The energizing frequencies were chosen in such a way that their harmonics did not coincide with each other or with the 50 Hz power line frequency.

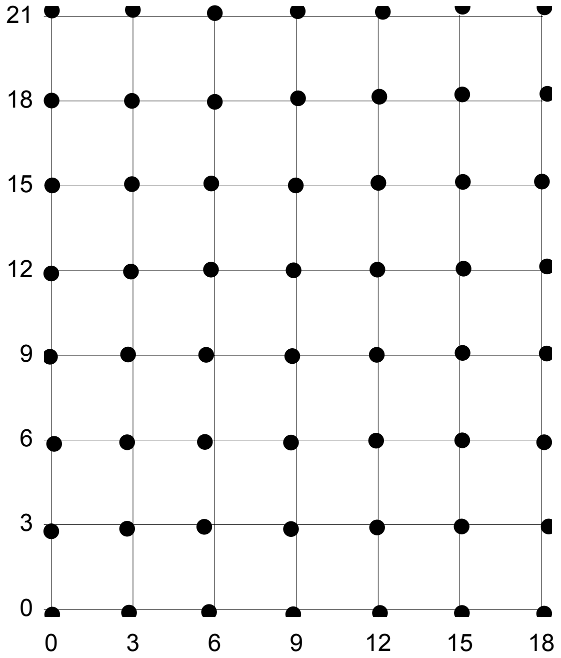

Figure 2. *A comparison of the positions of the fourth coil relative to the first three fixed coils to the theoretical grid. Systematic shifts and rotations have been eliminated by fitting the theoretical grid onto the coil positions.*

4.1 General accuracy of the method

The accuracy of the method was determined experimentally by fixing three coils on a piece of wood, on which a rectangular grid of 7 by 8 points with a 3 cm mesh size was depicted. A fourth coil with tip was used to indicate each grid point. The coils were energized with sinusoidal currents with frequencies of 5, 7, 12 and 17 Hz. The average distance between the coil set and MEG sensors was 30 to 40 cm.

For each grid point, all four coils were localized with the method explained in the methods section.

To obtain a measure of the accuracy of the method, a theoretical grid of the same dimensions as the one designed on the piece of wood was fitted point to point to the positions of the fourth coil. Then the average distance between corresponding points of the theoretical and fitted grid was computed.

Two experiments were performed, one in which the piece of wood was fixed and another in which it was moved several times in order to simulate patient head movement. In the first experiment, the average distance to the grid was .22 cm and in the second one, it was .24 cm. The distribution of the measurement points is shown in figure 2. No systematic increase of the errors near the grid boundaries can be observed.

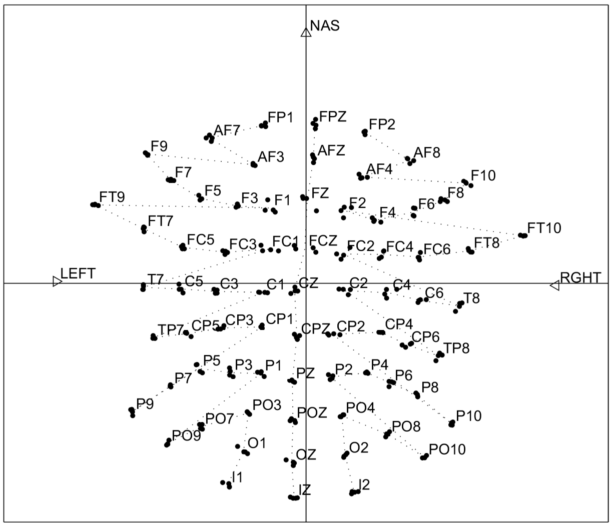

Figure 3. *An example is shown of electrode positions, measured with the proposed MEG digitizer. Each electrode was measured four times after another, in order to quantify the reproducibility of the measurements.*

4.2 Electrode positions

The method was also applied to determine electrode positions on a subject's head in a combined EEG/MEG experiment. In this experiment, MEG compatible electrodes were used mounted on a nylon EEG cap. Three coils were fixed on the nasion and the left and right pre auricular points. The fourth coil with tip was used to depict the electrodes. The subject was instructed to keep the head fixed during the 2 s needed to energize the coils and collect the data, but was allowed to move the head freely between measurements.

The reproducibility was determined by measuring, with the same subject, all electrode positions four times after another. Of these electrode positions the average positions were determined (w.r.t. the nasion-ear coordinate system) and of each individual measurement the distance to the average position was determined. It was found that the average of these individual distances over all electrodes amounts to .23 cm. It was also found that the largest variability was at the mid-saggital plane.

In figure 3, the resulting electrode positions are shown in the nasion-ear coordinate system, using a spherical projection. One observes that the cap was not placed exactly symmetrically on the head. For that reason, the symmetry line of the electrode grid is slightly rotated to the right.

4.3 Headshape

The MEG 3D localizer was also used to determine the shape of the head in the coordinate system of the MEG device. Figure 4 shows an example. The raw data set consisted of 248 points. Of this data set all points for which either nasion-left ear, nasion-right ear or left ear-right ear distances deviated more than .5 cm from the average were omitted, as well as all points for which the estimated coil callibration (=|**m**|) deviated more than 2 % from the average. After this omission 190 high quality points remained. For visualization, the points were connected by Delaunay triangles and only triangles appearing on the foreground are plotted. The figure shows that the digitized points are nicely distributed over the head shape surface.

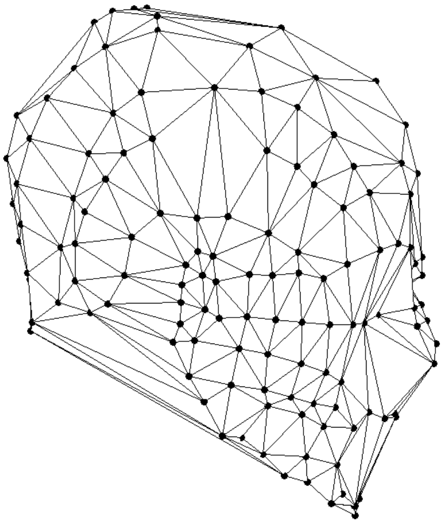

Figure 4. *The head shape measured with the four-coil method.*

5. Discussion

Compared to the methods described in [1] and [3], our method has the advantage that simple coils can be used, instead of three orthogonal and equally calibrated coils having their dipole moments at the same position. One advantage is that construction errors, giving rise to systematic localization errors, are avoided. Another advantage is that not only the coil position is determined, but also its orientation, which makes is possible to attach a tip yielding a well defined localization point.

The advantage of expressing the position of the fourth coil with respect to three other three coils which are localized each time the fourth coil points to a new spot is that the subject may move his head between the measurements. When a single Polhemus device is used instead, the subject's head has to be fixed during the whole measurement session.

6. References

[1] M. Fuchs, H.A. Wischmann, M. Wagner and J. Krüger, "Coordinate system matching for neuromagnetic and morphological reconstruction overlay", *IEEE Trans. Biomed. Eng.* **42**(4), 416-420, 1995.

[2] M. Singh, R.R. Brechner, V.W. Henderson, "Neuromagnetic localization using magnetic resonance images", *IEEE Trans. Med. Img.* **11**(1), 129-134, 1992.

[3] F. Incardona, L. Narici, I. Modena and S.N. Erné, "Three-dimensional localization system for small magnetic dipoles", *Rev. Sci. Instr.* **63**(9), 4161-4166, 1992.